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MOTION SICKNESS SIDE EFFECTS AND AFTEREFFECTS OF IMMERSIVE VIRTUAL ENVIRONMENTS CREATED WITH HELMET-MOUNTED VISUAL DISPLAYS

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ABSTRACT

We have investigated side effects and aftereffects evoked by moving the head to interact with a virtual environment (VE) shown in a helmet mounted visual display (HMD). The graphics computer of such a VE must monitor the HMD's spatial orientation and position in order to present images from the proper perspective. Delays between head movements and image updating cause aberrant visual motion of a virtual world. We found that above delays of 40 ms motion sickness and postural instability are evoked minutes after head movements begin. The severity of side effects is a function of the latency between head movement and visual update delay. Fifteen minutes of making head movements in a VE with a 254 ms delay causes motion sickness severe enough to make 28% of subjects withdraw from the situation. Users appear recovered 15 minutes after VE exposure ends if they remain immobile, but normal activities quickly revive their motion sickness symptoms, indicating that they were sensitized by exposure to visual update delays. We conclude that visual update delays are a unique cause of side effects and aftereffects in VEs utilizing HMDs.

INTRODUCTION

Virtual environment (VE) technology has many potential applications but current technology leads to side effects and aftereffects for users. Motion sickness is an acknowledged problem in VEs (DiZio & Lackner, 1992, 1997; Wilson, 1996) that needs to be solved because it is aversive and hinders performance of normal activities after the user leaves the VE.

We have attempted to document the incidence and etiological factors of motion sickness side effects and after effects associated with a prevalent VE configuration which utilizes an HMD. For experimental investigation, we developed a facsimile of the VESUB system developed at NAWC-TSD in Orlando, Florida for training naval candidates to navigate a surfaced submarine in a harbor. Subjects view a virtual harbor scene from the perspective of a surfaced submarine. One sub-goal of both VESUB and of real officer of the deck training, is for the user to develop spatial awareness by scanning the environment for signs and landmarks spread out over 360°. Therefore, the VESUB system and our experimental system utilize HMDs, which enable presentation of a panoramic view of the virtual world from a perspective that can be adjusted by glancing about in a natural manner.

The scenery of a virtual world in an HMD is carried around by the head instead of staying fixed like the real scenery. In such VEs, head position is monitored by a tracking device and fed to a graphics computer which updates the user's perspective and computes the proper image for the HMD display units. This gives the appearance of a stable virtual world and appears to contribute to the sense of immersion in the VE (Deisinger, Cruz-Neira, Riedel, & Symanzik, 1997). However, the process is imperfect in practice because of delays in the tracking device, the transmission of tracker signals, graphical computation and rendering time and others. These delays cause aberrant slippage of the retinal image when a head movement is made. That is, the HMD images commence moving later than the head and continue for a latent period after the head movement is complete.

In flight simulators utilizing large screen displays, motion sickness and postural instability are prevalent side- or aftereffects, but head movements per se have never been identified as etiological factors (Kennedy, Hettinger, Lilienthal, 1990). In our VE, the first and most obvious thing we noticed was that users rapidly became motion sick when they looked about wearing the HMD but did not complain if they kept still while viewing a stationary virtual world. The only visual motion in our VE was brought about by delayed updating of the visual scene in the HMD during head movements. Thus, we launched an effort to determine whether visual update delays associated with head movements are a specific cause of side-effects and aftereffects in VEs utilizing HMDs.

VE SYSTEM CHARACTERISTICS

VE computer and software: The virtual environment we experimented with was generated with a Silicon Graphics ONYX Reality Engine II computer (SGI). The virtual world was a harbor scene from the perspective of the sail of a surfaced submarine. The boat was still in the water, and there was no wave motion or any other external visual motion. The harbor channel was marked by buoys in the water and range markers on land. Geographic features, clouds and the water surface provided ample visual contrast. The HMD model we used was a LEEP Cyberface II. The LEEP has LCD displays 479 pixels wide by 234 high and uses optics which preferentially magnify the periphery of each LCD image. We used a psychophysical technique to determine that the LEEP FOV is 128° wide by 74° high, with 30° of binocular overlap. We calculated an angular resolution per pixel of 9.8 arcmin in the center graduated to 19.5 arcmin at the edges. In all our experiments, the rate of computing video frames was 30 Hz. The devices we used to track HMD position were a Polhemus 3SPACE FASTRAK magnetic device with a 19.2K baud serial interface or a custom-made mechanical device connected directly to the VME bus via an A/D board. We measured the end-to-end visual update delay of the system with both tracking devices. A PC computer recorded signals from photometric devices picking up activity directly from the IIMD display units and angular rate sensors on the HMD shell, while the VE was running on the SGI. The minimum delay we could achieve between onset of HMD movement and image movement on the HMD displays was 67 ms with the Polhemus and 21 ms with the mechanical device. We purposely added delays to the VE with a software ring buffer in order to achieve an adequate range of experimental visual update delays.

EXPERIMENTAL PARADIGM

Two separate experiments were conducted. The first experiment assessed motion sickness severity at visual update delays of 67, 159, 254 and 355 ms utilizing the Polhemus tracking device. Twenty one subjects participated in all conditions. Seven new subjects were recruited for the second experiment in which motion sickness severity was assessed at update delays of 21, 39, 80 and 163 ms, achieved with the mechanical tracker.

Experimental exposure to the VE lasted 15 minutes, split into five 2 minute sequences of head movements divided by 1 minute periods for rest and recording of motion sickness symptoms. In the 2 minute sequences, a pre-recorded audio tape announced landmarks in the VE for the subject to look at every five seconds (24 total movements). The required head movements ranged from 12° to 180° amplitude in the horizontal plane, between 25° up and 15° down in pitch. Subjects had been shown an aerial view of the virtual harbor before donning the HMD in order to familiarize them with the landmarks. The subjects stood while doing the task and most of the HMD's weight was supported by long elastic cords. Typically, subjects took less than one second to turn to a new target, using a combination of eye, head and torso rotation and sometimes shifting their feet, and then they stood still until the next landmark was called.

Acute symptoms of motion sickness were evaluated according to the criteria of Graybiel, Miller, Wood & Cramer (1968). The checklist derived from this scale measures five cardinal signs and symptoms of motion sickness, including nausea, pallor, sweating, salivation and drowsiness, and additional qualifying symptoms such as headache, dizziness and eye strain. Scores in the 8-15 point range indicate severe malaise. The checklist was filled out after each two minute sequence of head movements in the VE and 15 minutes after leaving the VE.

MOTION SICKNESS SIDE EFFECTS IN THE VE

Figure 1 illustrates the most severe motion sickness recorded during the 15 minute VE exposure period, for both experiments. The severity of symptoms increases monotonically as a function of the visual update delay. Analysis of variance indicated significant effects of visual update delay: $F(3, 60) = 10.43, p < .0001$ in Experiment 1 (67, 159, 254, 355 ms delays) and $F(3, 18) = 7.11, p < .0067$ in Experiment 2 (21, 39, 80, 163 ms delays). The severity of symptoms is significantly greater than zero at every delay except 19 ms ($p < .03$ at least, individual t tests). The ratings register from mild malaise on the Graybiel scale at 39 ms to moderately severe malaise at 355 ms. The severity of motion sickness seems to asymptote between 254 and 355 ms (no significant difference between these two). In the 254 ms delay condition, 6 of 21 of subjects (28%) refused to complete the full 15 minute exposure because they were too close to vomiting. The full spectrum of symptoms was reported in all conditions.

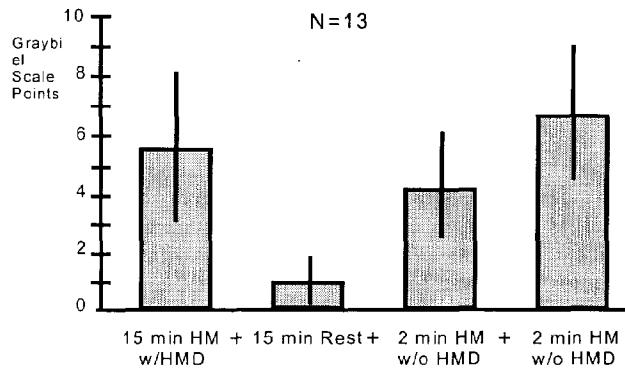


Figure 1. Motion sickness elicited by voluntary head movements (HM) in the initial 15 minute exposure to a VE with a 254 ms delay in update of the HMD image, after 15 minutes of rest without the HMD, 2 minutes of HM in a natural environment and 2 minutes in the VE again.

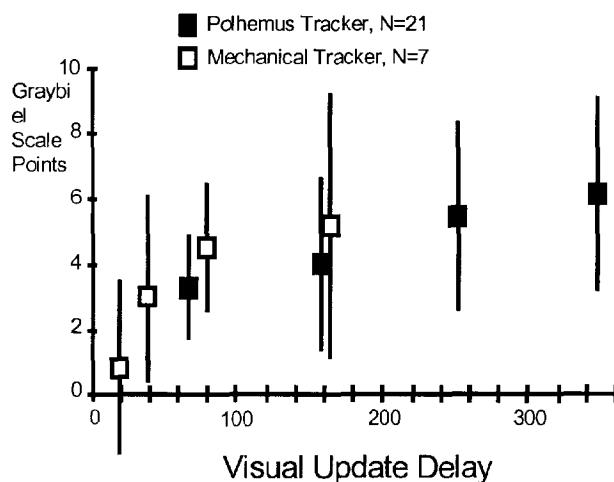


Figure 2. Motion sickness severity as a function of visual update delay, in VEs created with two different tracking devices. The plot shows the maximum severity rating evoked during 15 minutes of intermittent voluntary head movements.

MOTION SICKNESS AFTEREFFECTS

A preliminary analysis of the first 8 subjects indicated that motion sickness symptoms had abated almost entirely in 15 minutes after the VE exposure period was over and the subjects had been resting quietly. Therefore, we asked the remaining subjects after the 15 minute rest period to perform two additional head movement sequences, guided by the same 2 minute tape recorded directions as before.

In the first post-rest sequence, the HMD was not worn and the location of VE landmarks was marked by tags placed on corresponding locations in the real laboratory environment. As soon as the motion sickness symptoms were recorded, the subjects donned the HMD again and made another 2 minute sequence of head movements in the VE and reported symptoms a final time. The extra conditions were only done after the 254 ms delay VE exposure. Figure 2 illustrates the complete pattern of results for the 13 subjects who completed all conditions.

The motion sickness severity experienced by this sub-sample during 15 minutes in the VE was 5.7 points, which is similar to the value of 6.2 for the whole sample. Fifteen minutes after leaving the VE and resting in a normal

environment the malaise level was only 1.0, not significantly above zero. Subsequently performing head movements in a natural environment for 2 minutes brought the motion sickness score back up to 4.4 points, which was significantly above 1.0. Returning to the VE and making head movements for 2 minutes brought the symptom level up above the level of the original fifteen minute exposure, to 6.7 points.

CONCLUSIONS

The results indicate that motion sickness is a serious potential side effect and aftereffect of using a HMD as a visual interface to interact with a VE. Motion sickness severe enough to convince subjects they might vomit can be elicited within minutes of exposure to the VE. Users experience no motion sickness unless they move their head to scan the environment. In the VEs we studied, there was no simulated motion of the user's base of support or of other objects. The only visual motion was generated by voluntary head movements. Thus, head movements are a sufficient cause of motion sickness in VEs incorporating HMDs. This is not the case in flight simulator.

Overt motion sickness decays quickly after a 15-minute VE exposure is over, but users remain sensitized. Anecdotal reports indicate the period of sensitization is much longer than the 15-minute period in which we have done formal evaluations; up to hours is possible. During the sensitized period, even normal activities can bring the symptoms back, and returning to the VE escalates symptoms immediately to the prior maximum level or above.

Lags between head movements and compensation of the image in the HMD are a powerful etiological factor in this form of motion sickness. Such lags distort visual motion of the virtual world during head movements. The motion is distorted in the sense that the normal coordination of the vestibulo-ocular and optokinetic reflexes does not result in stabilization of the retinal image. The magnitude of aberrant visual motion and the severity of motion sickness both increase in proportion to the visual update latency. A latency of 19 ms is below threshold for eliciting motion sickness, under the conditions we tested.

These findings can aid in ameliorating or circumventing motion sickness in VEs. They suggest that careful measurements of end-to-end visual update delay of VE systems is necessary to anticipate and circumvent side effects. To avoid motion sickness, users can limit their head movements, VE designers and engineers can strive for sub-threshold visual update delays, or the power of human sensorimotor adaptation can be exploited.

We are currently attempting to define other etiological factors and side effects that must be taken into consideration. Our results indicate that postural instability is another serious side effect/aftereffect and that the field of view, weight and spatial resolution of an HMD as well as the computation rate of video frames are other etiological factors.

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